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Time Structure of the Slow Extracted Beam for the Booster Applications Facility

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Contents

1 Time Structure Formalism

definitions:

Q = horizontal betatron tune

ξ = horizontal chromaticity = $\frac{dQ/Q}{dp/p}$

I_m = current in the Main Dipoles and Quadrupoles

N = number of particles ($\frac{dN}{dQ}$ represents the particle distribution in tune space

T = period over which particles are extracted

Low frequency duty factor:

$$D_f = \frac{[\int_T S(t)dt]^2}{T \int_T [S(t)]^2 dt} \Rightarrow (\frac{f_{av}}{f_{rms}})^2 \;\; in\ general$$

where

$$S(t) = \frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt}$$

if there is no ripple,

$$S(t) = \frac{dN}{dQ}\dot{Q}_0$$

where $\dot{Q}_0$ is the rate at which particles move into resonance.

$$\dot{Q}_0 = \frac{Q\xi}{I_m}\frac{dI_m}{dt}$$

If there is ripple on the magnet power supplies;

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v)$$

where $\dot{Q}_v$ is the variations in the rate at which particles move into resonance.

$$\dot{Q}_v = \frac{Q\xi}{I_m L_m}\sum_h V_h$$

L_m is the total inductance of the main dipoles and quads and V_h is the sum of the 60 Hz harmonics amplitudes (in volts).

2 Evaluation of Booster Harmonics

Constraints:

1. Beam size at full energy is about 1cm.
2. Max. Dispersion, $D_{max} = 3$m
3. Chromaticity at Extraction can be about -2

What is max. dp/p ?

$$D_{max}\frac{dp}{p} \leq 3\ cm\ ,\ then\ \frac{dp}{p} \leq 1\%$$

What is max. dQ/Q ?

$$\frac{dQ}{Q} \ = \ \xi\frac{dp}{p} \ \leq \ -0.02$$

In this case $dQ \leq 0.09$.

We have two competing components:

$$\dot{Q}_0 = \ \frac{Q\xi}{I_m}\frac{dI_m}{dt}$$

and

$$\dot{Q}_v = \ \frac{Q\xi}{I_m L_m}\sum_h V_h$$

For a 1 second spill we expect $\dot{Q}_0$ to be -0.09 and,

$$\dot{Q}_v = -0.0119 \sum_h V_h$$

The "best" we can do is approximately $\Sigma_h V_h =$ 18 volts.

Then,

$$\dot{Q}_v = -0.214$$

The result is a fully modulated beam spill for a 1 second beam. For 500 ms it will still be fully modulated.

Current AGS spill for 1 GeV/n Iron is about 50 % modulated.

3 Time Structure from other devices

There are 4 main sources:

1. Trim Quadrupole P.S.'s
2. Drive Sextupole P.S.'s
3. Chromaticity Sextupole P.S.'s
4. Orbit Bump P.S.'s

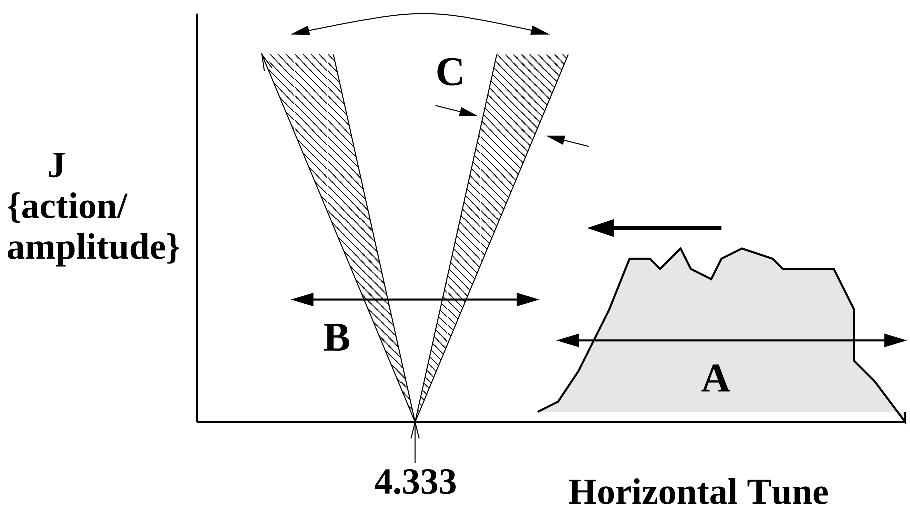


Figure 1: Steinbach Diagram for 1/3 integer resonance

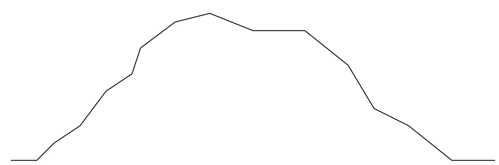
(A) Beam motion, from main field ripple

(B) Tune "wobble"; quads, sextupoles and bumps

(C) resonance variations, drive sextupoles

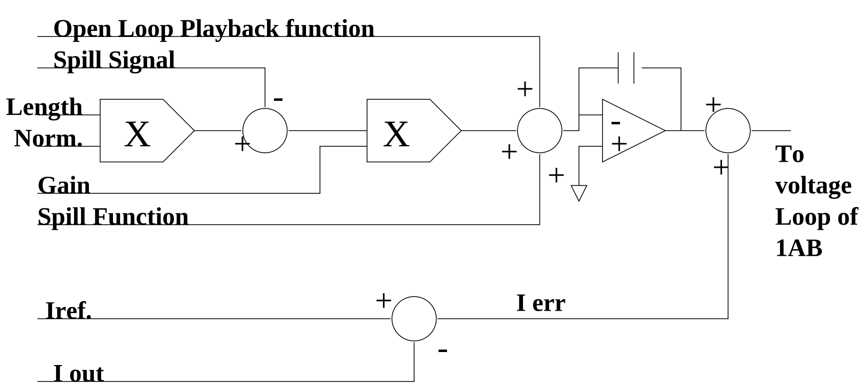
4 Slow Spill Servo

The main purpose is to act on $\frac{dN}{dQ}\dot{Q}_0$ to create a constant current beam distribution.



Spill for a Linear dQ/dt

Spill in which dQ/dt is matched to dN/dQ



5 Modifications to Booster Main Magnet for Spill Control

1. Software for control of the Booster Main Magnet P.S. is being updated.
2. An Active filter will be added (using one of the old Trim Quad P.S.'s)
3. New PT's (potential transformers) will be bought, to allow good ripple measurements

Studies to be performed, will look at:

1. new software performance
2. performance of main magnet P.S. and transformers with a 1 second flattop up to 5000 amp.
3. ripple reduction (tuning phase firings)

In addition beam studies to be performed.

1. Looking at frequency of radial oscillations on the flattop.
2. If possible, create a resonance and observe structure on a beam counter.

6 Time Structure Correction System

In this case we create a new term $\dot{Q}_c$, that tries to be equal and opposite to the $\dot{Q}_v$ term.

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v - \dot{Q}_c)$$

How ?

1. use independent set of quadrupoles and P.S.
2. use existing quadrupoles and existing P.S.
3. feed-forward into these quads known P.S. harmonics; adjusting gain and offsets.

$$\dot{Q}_c = 0.2 \ \ \Delta Q \ in \ 1 second.$$

The fastest possible swing from minimum to maximum of about $\delta\nu = 0.0033$ is in 60 Hz.

Two possible designs:

1. Add a set of dedicated quadrupoles.

   After every Booster dipole is a 0.57 m straight section with β_{max} = 12.5 m

   β at trim quads (horizontal) = 14.1 m

   Build 12 quadrupole magnets; 0.25 m, 5 turns

   $$\frac{\Delta Q}{\Delta I} = \frac{0.25}{0.5} \times \frac{12.5}{14.1} \times \frac{12}{24} \times 5 \times (\frac{\Delta Q}{\Delta I})_{trims} = 6.6x10^{-4}$$

   Suppose inductance = 5 x 10^{-3} H, then to get ΔQ = 0.0033 we need +/- 5 Amp/60 Hz at 9.5 volts.

Magnets Est. Cost: $ 100-200 k

2. Use existing quadrupoles.

In this case $\frac{dQ}{dI}$ = 6 x 10^{-4} and inductance = 7.5 x 10^{-4}. Now we need +/- 5.5 Amp/60 Hz at 1.5 volts.

7 Reducing Time structure using RF Phase Displacement

From

$$S(t) = \frac{dN}{dQ}\dot{Q}_0(1 + \frac{\dot{Q}_v}{\dot{Q}_0})$$

For 1 particular frequency we can write the duty factor as

$$D_f = \frac{1}{1 + \frac{1}{2}(\frac{\dot{Q}_v}{\dot{Q}_0})^2} = \frac{1}{1 + \frac{1}{2}(\frac{\omega \delta Q}{v_0})^2}$$

where

$\omega =$ frequency

$\delta Q =$ relative ampl. of that freq. in tune space

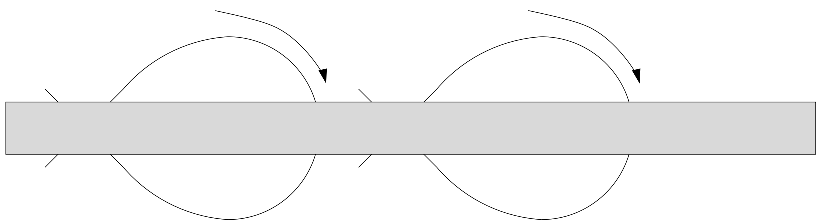
$v_0 =$ speed that beam crosses resonance

$$v_0 = \frac{\Delta p}{p}\frac{1}{T}$$

D_f is increased by

1. decreasing δQ
2. increasing v_0

One way to increase v_0 is to increase $\frac{\Delta p}{p}$. To further increase it we use RF phase displacement, using a high frequency RF cavity. In this case RF buckets are centered on the resonance.



The buckets are empty and beam is forced between them.

Now,

$$D_f = \frac{1}{1 + \frac{RB\rho T}{V\frac{\Delta p}{p}}(\omega\delta Q)^2}$$

Without RF phase displacement, a 100 % modulated spill has $D_f = 0.67$. In this case,

$$\omega\delta Q \geq \frac{\Delta p}{p}\frac{1}{T}$$

With RF phase displacement, a large $\omega\delta Q$ is easily corrected.

Consider for the Booster:

$B\rho = 17$ Tm

R = 32.11 m

V = 10 kV (voltage on high frequency cavity)

T = 1 sec.

$\omega\delta Q = 0.01$

Now $D_f = 0.99$!

8 Time Structure and Correction for Bunched Slow Extraction

With RF on and $\frac{dB}{B} = 0$,

$$\frac{df}{f} = -\eta \frac{dp}{p}$$

where

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}$$

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v - \dot{Q}_{rf})$$

$\dot{Q}_{rf}$ is the modulation of df/dt to compensate for $\dot{Q}_v$.

$$\frac{dQ}{dt} = \frac{dQ}{dp}\frac{dp}{dt} = \frac{Q\xi}{f_{rev}\eta}\frac{df_{rev}}{dt}$$

We know that $\dot{Q}_v = 0.2$.

$$\dot{Q}_0 = \frac{Q\xi}{f_{rev}\eta}\frac{df_{rev}}{dt} = Q\xi\frac{\Delta p}{p}\frac{1}{T} = 0.025$$

(for a $\frac{\Delta p}{p} = 0.29$ %, the bucket height)

To correct for $\dot{Q}_v$ for all harmonics the radial loop servo bandwidth must be below the synchrotron frequency (9 kHz).

The system must be capable of correcting such that $\dot{Q}_v - \dot{Q}_{rf} \ll \dot{Q}_0$ in order to get a good spill.

9 Summary

Power Supply Ripple will cause 100 % modulated beam. Currently in AGS spill is 50 % modulated.

1. Three methods for reducing the spill structure were shown
   (a) Time Structure Correction System.
   Potentially Improves spill to 50 % or better.
   Cost to add new quads is expensive, modifying existing system is an option for little additional cost.
   (b) RF Phase Displacement.
   Improves spill to 10 - 20 % modulation or better, given AGS experience.
   Cost is approximately $ 100-200 k. There is room in Booster for it.
   (c) Bunched Slow Extraction.
   Not enough is known, from a practical perspective, on how well this will work.
   Cost may be expensive, since it not only requires slight modifications to the Low Level RF, but also requires modifications to the

high level RF system to allow keeping the high voltage on during the flattop.

2. We will learn more when we get to do real machine and beam studies.